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Gentlemen,

Our first Progress Report on "A Laser-Based Surface Reconstruction Device for Oceanographic Measurements" is enclosed. This is delivered in response to data item number 0001AA of contract N00014-98-C-0143. As required by our contract, copies of this report have been to the Program Officer, Director, Naval Research Laboratory, and the DTIC. A copy of this transmittal letter has been forwarded to the Administrative Contracting officer. If you have any questions please call me at your convenience.

Yours truly



Jiangying Zhou
Director of R&D

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Progress Report I

A Laser-Based Surface Reconstruction Device for Oceanographic Measurements

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1. Overview

For many applications related to the Navy's mission, it is of interest to obtain information about a water surface. For example, the surface of the ocean reveals information about the underlying ocean floor. This is important for landing operations and ship navigation. Another example involves the use of LIDAR to obtain information about objects beneath the water surface. The scattering of the light used for such an application depends on the characteristics of the surface. For instance, according to Snell's law the refraction of the light depends on the slopes of the water surface. Hence, to obtain accurate information about the object beneath the water surface, it is often desirable to know the slopes of the surface at the moment of measurement, and sometimes, the complete description of the surface.

The water surface is formed by larger gravitational waves as well as smaller capillary waves superimposed on the gravitational waves. The primary goal of this project is to design, build and field test a device suitable for obtaining the shape, and in particular, the slopes of the larger waves. The target application for this device is an LIDAR-based system, mounted on a helicopter, used for detecting underwater targets. By using the slopes provided by the device, it will be possible to correct for the refraction distortions due to the gravitational waves and obtain a more accurate location estimation of the target.

2. Test Paradigms

We have completed the initial feasibility study for the project. Five measurement paradigms for determining the shape of a water surface have been identified. Four were deemed realizable and will be explored further. The main effort will be focused on the *Point-Source Diffuse* method. However, the other three paradigms shall also be explored during the course of the experiment. Since all methods share essentially the same equipment components, (The first, third, and fourth paradigms, for example, are based on stereo vision principle and all involve imaging water surface using multiple cameras under a single light source), it is cost effective to explore multiple paradigms in parallel.

2.1. Specular Reflection Method

The simplest paradigm from an experimental standpoint is to image specular reflection from low frequency, large amplitude water waves taken from two or more vantage points. These images provide information about the surface normal of the waves from multiple viewpoints. From this the total shape can be reconstructed. The primary advantage of this method is that very low power light sources can be used to capture specular reflection. The drawbacks of the approach are that the calculation may be confused by multiple reflections at the surface, and that certain configurations of the surface may result in little or no specular reflection. Experimental observation will be needed in order to determine the feasibility of the method.

2.2. Diffuse Surface Photometric Method

A second paradigm, which was originally proposed, is to use the photometric approach. Under this approach, several light sources are used to illuminate the water surface. For each light source a picture is taken of the surface from the same point of view. From the intensity information in the images, the surface normals can then be calculated.

The photometric approach relies on the assumption that water is a diffuse surface. On the other hand, water is diffuse only when it is in a very turgid state. One possible solution is to perturb the water surface

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by some mechanical intervention, such as firing bullets at the water using a large scattergun. Once disrupted, the surface can be photographed from the same viewpoint with multiple illumination sources. The difficulty here is to develop a scheme for disturbing the waves to create sufficient diffuse characteristics without destroying the shape of the waves. This issue shall be explored in the course of our experiment.

2.3. Point-Source Diffuse Method

The approach we shall be focusing on primarily is to generate *point-source diffuse reflection* or isotropic scattering on the water surface by mechanical intervention. This can be accomplished by perturbing the surface with a spray of water or with pellets from a scattergun. The point-source reflection serves as control points of a mesh covering the surface of the water. Two or more cameras positioned at different vantagepoints record the locations of these points. A triangulation method is then used to recover the surface characteristics of the water (See Figure 1).

This method has the advantage that one can control the mesh coverage for triangulation, thus control the probability of error. In addition, equipment set-up is simpler than the second method, as it is explained later. Its drawback is that more powerful light sources are needed in comparison to the first method.

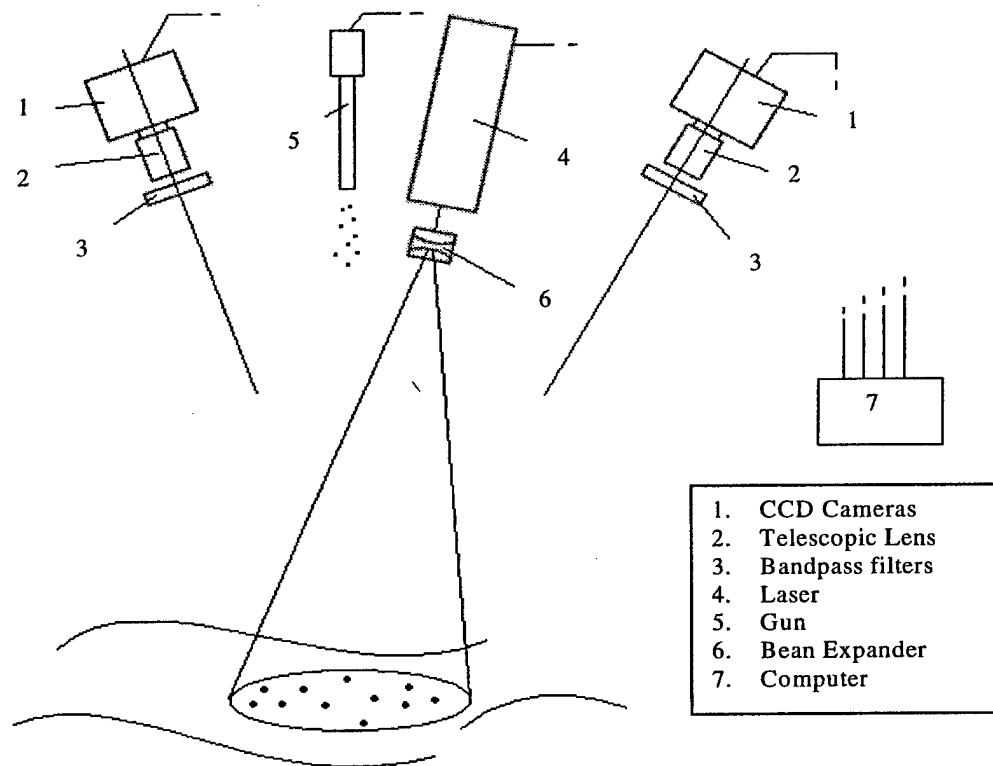


Figure 1: Equipment configuration for surface measurements.

2.4. Triangulation from Capillary Waves Method

A fourth method is triangulation on specular reflection from capillary waves on the water surface. Again, low-power light sources can be used, and if we assume that there are sufficient "point" reflectors (capillary waves) on the surface to uniformly cover the surface then a mesh can be developed based on triangulation of these reflectors. The surface shape can be reconstructed from this mesh of point reflectors.

This approach is similar in concept to the third method, with the advantage that no disturbance is introduced to the surface of the water. The drawback of this method is that it is possible that there will be insufficient "point" sources for a complete mesh. Furthermore, the mesh points cannot be controlled, such

as the case in the third method. Again, experimental evaluation shall be conducted to determine the merits of this approach

2.5. Spinning Reflector Method

Finally, we shall mention here a method that, in our judgement, is not feasible at the current time. The idea is to use a spinning reflector to create multiple specular snapshots (*e.g.*, 360 spherical rotation) of the water surface, all from the same viewpoint. The high intensity lines generated in the images indicate surface normals parallel to the reflected laser. The remaining points can then be interpolated. Unfortunately, even though the method is computationally simple, the size of the spherical reflection mirror required by the method is too large for a helicopter to handle.

3. Equipment Requirement

We divide the equipment components for the experiment into three categories: illumination, imaging and analyzing/control. The details of each are explained below.

3.1. Illumination Equipment

Illumination options include continuous sources and pulsed sources, of which we have selected pulsed systems for our prototype. Continuous sources (such as lamps and CW lasers) would require precision time-gated imaging in order to have any hope of acquiring an image of a specific surface wave configuration. In addition, while CW sources have relatively high average powers, their peak powers are relatively low and this constitutes an experimental problem. For example, if we presume the presence of a mechanical vibration with a frequency of 5 kHz during data acquisition, surface images should be acquired from two or more vantage points for triangulation within a period of less than 100 microseconds in order to minimize image blurring. If the optical source provides 1 Watt of usable light, the power delivered during this imaging period is 100 microJoules, approximately 10^{12} photons. If this is dispersed over a water surface with an area (in our test) of approximately 10^5 cm^2 , the photon density in the imaging period is $10^7 \text{ photons/cm}^2$.

A typical lens located at a distance of 10 meters (as in our test) subtends a solid angle of approximately 0.01 steradians. If scattering is isotropic into 4π steradians, less than $10^4 \text{ photons/cm}^2$ will be returned to the imager. Given typical efficiencies of imaging systems and lenses, we can expect to detect approximately 10^3 photons from each cm^2 of scattering surface. With most imaging systems, this will be acceptable, if marginal. However, our aim is to eventually develop this prototype for longer-range imaging, up to 150 meters. The photon flux diminishes as the square of distance, and this would reduce the detected photons to only 5 per cm^2 , too little to be usable. When the difficulty and expense involved in time gating an imager to sub-100-microsecond integration times is considered, continuous sources are therefore inadequate for our task if non-specular reflection is the primary means of triangulation.

Pulsed laser systems solve many of these problems. The low-power pulsed laser we have selected (Continuum Minilite II, 25 milliJoules/pulse, 5 nano-second pulse-width) is relatively dependable, will produce $2 \times 10^6 \text{ photons/cm}^2$ at the detector in our test, and can eliminate the need for precise time gating of the detectors. At 150 meters, a more powerful version (Continuum Surelite I, 200 milliJoules/pulse, 5 nanosecond pulsewidth) would generate a return of $10^4 \text{ photons/cm}^2$, compared to the 5 estimated above for a CW source.

The likelihood of mechanical vibration during actual implementation of the system also means that the approach of illuminating the water surface from two or more angles can be subject to a great deal of error. Therefore, this is not considered a realistically practical concept.

3.2. Imaging Equipment

Imaging systems can be constructed in at least two different ways. The first way is to use a single camera to record images from two vantagepoints using mirrors — the typical rangefinder arrangement. The other method is to use multiple cameras. In our prototype, this is deemed more practical according to the following error analysis.

The error in position calculation using triangulation is given as:

$$dD = \frac{-D^2}{B} d\theta$$

where D is the distance to the target, B is the baseline separation of the vantage points, and $d\theta$ is the error in angular measurement. Assuming an electronic detector, $d\theta$ is defined, at best, by the angle subtended by a single detector pixel. If we assume an imaged area of 2.5 meters (conditions of our test) and a detector with 500 pixels (typical), $d\theta$ is approximately $0.5\text{cm}/D$. Incorporating a desired error in distance of less than 5 cm, this equation reduces to:

$$B \geq \frac{D}{10}$$

At a target distance of 10 meters, the required baseline separation in vantage points is at least 1 meter. This is reasonably achieved with mirrors. However, in eventual applications at 150 meters the separation required increases to 15 meters, and this is not practical with mirrors in most realistic scenarios. Consequently, we have decided not to pursue this avenue in the prototype, choosing instead to use two different cameras that can be conveniently moved to different baseline separations.

We have selected back-illuminated thermoelectrically cooled low-noise full-frame CCD cameras manufactured by Hamamatsu, Inc. for this imaging application. This choice was made because these cameras can integrate for long times without accumulating significant dark signals, making the timing of the system less critical. In addition, they have quantum efficiencies near 80% at the laser wavelength of 532 nm, between 4 and 20 times better than typical detectors. Shutters manufactured by Vincent Associates (Uniblitz D-122, minimum exposure of 30 milliseconds) and laser bandpass filters blocked throughout the camera's range of optical sensitivity (Omega Optical, Inc. 532 bp 40) will be provided for each camera to screen out ambient light.

3.3. Control and Analysis Equipment

The complete system for the field will be programmed in the LabVIEW programming environment for ease of construction and operation. All hardware (camera shutters, laser trigger, and camera readout) will be controlled through a National Instruments DAQ-16E-4 PCMCIA card installed in a laptop computer, while image reconstruction will be performed with a compiled C library linked to the LabVIEW code through a Code Interface Node. Image presentation will be performed with National Instruments IMAQ Vision VIs. In addition, we shall use a high-end graphic computer for computation-intensive 3-D simulation.

3.4. Equipment Cost Break-down

Illumination Equipment	Unit	Unit Price	Total Cost
Pulse Laser	1	\$16,000.00	\$16,000.00
Bandpass Filter	3	\$ 300.00	\$ 900.00
Scattergun			\$ 5,000.00
Miscellaneous Parts			\$ 5,000.00
Imaging Equipment			
Digital Cameras	3	\$ 5,000.00	\$15,000.00
Shutters	3	\$ 1,000.00	\$ 3,000.00
Analyzing/Controlling Equipment			
Graphics Computer	1	\$18,000.00	\$18,000.00
Notebook Computer	1	\$ 4,300.00	\$ 4,300.00
LabView Software	1	\$ 2,000.00	\$ 2,000.00
Advanced IMAQ Vision Software	1	\$ 1,000.00	\$ 1,000.00
Structural Environment			
Miscellaneous Parts			\$10,000.00
Total			\$80,200.00

4. Computational Methods

The surface reconstruction problem here can be broken down to two computational problems: The first is the stereo vision problem of determining the height of the surface from multiple images at different locations. The second is the surface reconstruction problem from a set of uniformly scattered height data.

Stereo vision is a well-established method for performing triangulation from two cameras to determine the distance (depth) of objects. It is based on the positions of a single point that appears in each image. Determining the points in one image in relation to the other, is the correspondence problem. This can be very computationally expensive. However, if constraints are placed and other stereo pairs are used, the search time can be reduced.

A sketch of the stereo vision setup is shown in Figure 2. A stereo pairs, points P_l and P_r in images I_1 and I_2 respectively, represents the projections of a point, P on the ocean surface onto the two camera imaging planes. If the global positions of the two image planes are known as well as the focal lengths and directions, then the position of the surface point can be determined. The surface point is at the intersection of the vector from P_l to its focal point with the vector from P_r to its focal point.

Given a large enough set of points, the surface can be reconstructed. However, there are difficulties if some information is incorrect, or the surface is not smooth. Given the height map for a subset of the points, the whole surface will be interpolated from those points using variational methods involving multi-resolution techniques subject to a smoothness constraint. The smoothness constraint makes sense for irregular waves, when the refraction problem is considered. The refraction problem is to correct the refraction angle from cameras given a view underneath the surface. Good views will only occur where the water is relatively smooth, and therefore, not at the apex of a crashing wave.

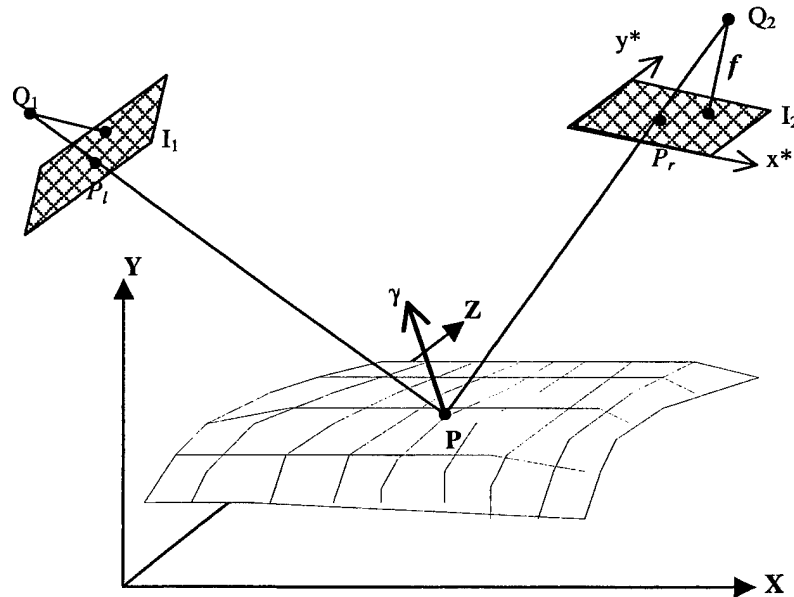


Figure 2. Stereo vision. γ is the surface normal at P . Q_1 and Q_2 are the focus points of the two cameras. f is the focus length.

5. Schedule and Milestones

The following is our tentative development and test schedule:

- **May – June:** Test device assembly
- **July -- August:** preliminary test in a controlled environment.
- **September – October:** field test.

A second progress report shall be submitted to Office of Naval Research by the end of August. In this report, we shall provide preliminary testing data verifying the feasibility of the proposed measurement designs and conducting comparative analysis. The test shall be done in a controlled environment. A final measurement design shall be chosen based on the test data. A field test shall then be conducted at DUCK in fall on the chosen method.